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TIME OF FLIGHT LIDAR MEASUREMENTS AS AN OCEAN PROBE

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13. ABSTRACT

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Photons emitted by a narrow laser beam are followed through multiple scattering events in the ocean until registered by a detector at the source position. A realistic ocean model is used which takes account not only of molecular scattering (Rayleigh) and absorption, but also scattering and absorption by the hydrosols (Mie). The single scattering function for the hydrosols is calculated from Mie theory assuming a relative index of refraction of 1.15 and a size distribution with a modal radius of 3μ. Targets with various surface albedos (A) are introduced at various distances from the source. The three dimensional path of the photons is followed by a Monte Carlo technique. When $A \geq 0.02$ the returned flux per unit photon path length from the targets is greater than the background from the laser beam for any target distance. The returned flux is plotted as a function of the photon path length. In practice the detection distance is limited by the lowest flux which can be detected and the background of natural light. Inhomogeneities in the optical properties of the ocean can also be measured in this way.

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Introduction

The distribution of the photons emitted in a pulse of radiation from a laser and subsequently scattered by the hydrosols as well as the Rayleigh scattering centers in the ocean provides important information about the properties and spatial distribution of these particles. In addition there is the practical problem of detecting an object at a given distance when illuminated by a laser source. Theoretical guidance in these problems has not been available since solutions of the usual equations of radiative transfer are not known when the source is a narrow beam. Lidar measurements beneath the ocean have been made, but no results have been published as yet.

This is an ideal problem for the Monte Carlo method, since the radiation at the detector can be calculated through all orders of multiple scattering for realistic phase functions that take account of the highly anisotropic scattering from typical hydrosols. The Monte Carlo method used here has been previously described by us when solar radiation is the source[1-5] and when a laser source is used in the atmosphere.[6] The interaction of the laser beam with water molecules and hydrosols is determined from single scattering functions. The probability of scattering through a particular angle is given by the appropriate single scattering function calculated from Mie theory[7] for various polydisperse distributions. The scattering angle is chosen from the appropriate single scattering function for each collision. In the present study the detector is always located at the position of the source. Model oceans with various amounts of turbidity are considered as well as targets with a range of surface albedos.

Method

The photons are emitted from the source uniformly into a cone with a half angle of 10^{-3} radians. The exact three dimensional path of each photon is followed in the computer experiment. The scattering angle is chosen from the appropriate single scattering function. At each collision a radiance is estimated at the detector. The detector is assumed to be located at the position of the source and to have a half width of 5×10^{-3} radians. At each collision a choice is made from an appropriate distribution function as to whether the photon is interacting with a hydrosol or a water molecule and whether the photon is scattered or absorbed.

A weight, initially unity, is associated with each photon. Collisions are forced so that the photon never leaves the ocean; the weight associated with the photon is changed each time a forced collision occurs so that the correct result is obtained. A trajectory is also never terminated because of absorption; instead the photon weight is again appropriately adjusted to include this possibility. The use of the concept of photon weights is one of several important techniques which are used to reduce the variance of the result. A photon trajectory is terminated only when its weight falls below a preassigned number, usually taken as 10^{-5}.

When a photon undergoes a collision with a Rayleigh scattering center, the scattering angle is chosen from the appropriate single scattering function ($\sim 1 + \cos^2\theta$). The single scattering function for the hydrosols was calculated exactly from Mie theory[7,8]. The particulate

matter in the water was assumed to have $n_1 = 1.15$ and $n_2 = 0.001$, where n_1 and n_2 are the real and imaginary parts, respectively, of the index of refraction with respect to water. A size distribution was assumed which is constant for $r < 1\mu$ and proportional to $r^6 \exp(-2r)$ for $r > 1\mu$, where r is the radius of the hydrosol. The modal radius for this particle size distribution is 3μ.

The single scattering function was computed from the Mie theory for particles with this size distribution and index of refraction. The result is shown in Fig. 1 of Ref. 9. The scattering function is highly anisotropic with strong forward scattering. These particular values of the hydrosol parameters were chosen after a study of the disparate values proposed in the literature[10-15]. Many different types of particles, both organic and inorganic, occur in ocean waters in varying amounts. The real test of our model lies in a comparison of the calculated single scattering function with experimental measurements and eventually of the calculated and measured radiation fields. Measurements of Beardsley[15] of the single scattering functions of natural hydrosols from ocean and coastal waters cover a range of scattering angles from approximately 10° to 130°. Within that range our calculated curve agrees well with the measurements for ocean water. This agreement provides some justification for the choice of parameters in our model. It also leads us to hope that the calculated values for scattering angles nearer 0° and 180° are approximately correct, regions where unfortunately there are as yet no experimental measurements.

Whenever a photon encounters a hydrosol the new scattering angle

is chosen in the Monte Carlo calculations from a cumulative distribution function calculated from the single scattering function. The model is completed by the specification of the ratios of the attenuation lengths β which determine the relative contributions of Rayleigh and Mie scattering and the fraction of radiation absorbed by each type of scattering center. The following values were assumed: $\beta_{S,R}/\beta_{T,R} = 0.567$, $\beta_{S,M}/\beta_{T,M} = 0.833$, and for $\beta_{T,R}/\beta_T$ a range of values from 1.000 to 0.0714, where β_S and β_T represent scattering and total attenuation lengths, respectively, and R and M represent the part due to Rayleigh and Mie scattering centers. These parameters should be representative of ocean water at $\lambda = 0.46\mu$ with varying degrees of turbidity. The ratio $\beta_{T,R}/\beta_T$ determines the amount of turbidity. (Note: in Ref. 9 due to a typographical error the value of $\beta_{S,R}/\beta_{T,R}$ is given incorrectly as 0.165; the value used in the calculation is 0.0165 at $\lambda = 0.65\mu$.)

Results

The results were calculated first for an ocean model with pure Rayleigh scattering; this corresponds to an unusually clear ocean with no appreciable hydrosol scattering. The returned flux as a function of the photon path length is given in Fig. 1. The returned flux is normalized to unit flux emitted by the source. In each case the returned flux is expressed as the total flux returned for all photons whose path length lies within a one meter path interval. Since the photon path length is the total distance covered by the photon from source to detector, it is proportional to the time delay between the sending of the pulse and its detection. The total attenuation length is assumed

to be 0.036 m^{-1}.

The circles shown in Fig. 1 indicate the calculated returned flux including all orders of multiple scattering when the target is located at 10 m. The returned flux from the target is indicated by the circles on a vertical line at a photon path length of 20 m. The numbers beside the circles indicate the albedo (A) of the target. In this case when A = 1, the returned flux from the target is several orders of magnitude greater than that returned by the scattering centers in the ocean near the target. Even when A = 0.01, the returned flux is significantly above the oceanic background.

Similarly the calculated returned flux is shown by other symbols when the target is at 30 m, 50 m, and 80 m. In each case the returned flux from the ocean for a given photon path length is nearly the same regardless of the position of the target. This oceanic background decreases with photon path length because of both exponential attenuation and the r^{-2} factor in the intensity. The small fluctuation in the Monte Carlo results is evident upon comparison of these four completely independent calculations. Within the assumptions of this calculation a target could be detected with equal ease at any distance provided only that the low level of the returned flux could be measured. However, no other light source than the laser has been assumed. At some point the returned flux could not be detected above the ambient light level in the ocean at the detector. It is interesting that a target can be detected in principal at any distance by this method.

Next the influence of photon scattering from the hydrosols in a

moderately clear ocean was considered. The ratio $\beta_{T,R}/\beta_T$ is chosen as 0.5. Thus in half of the collisions the photon interacts with a hydrosol and in the other half with a Rayleigh scattering center. The attenuation length is assumed to be 0.072 m^{-1}. The results are given in Fig. 2 for targets at 10, 30, 50, and 80 m. The returned flux decreases more rapidly with photon path length when hydrosol scattering is included. Also the flux returned from the target is not only smaller, but is closer to the background from the oceanic scattering. The points for a target with A = 0.01 are only slightly above the background.

A ratio $\beta_{T,R}/\beta_T$ = 1/14 is assumed for the next case in order to study the laser scattering in very turbid ocean or coastal water. The results are given in Fig. 3 for targets at 2, 5, and 10 m. Since the attenuation length is now 0.216 m^{-1}, the photons can not penetrate a great distance in this turbid water. The returned flux decreases much more rapidly with photon path length compared to the previous cases. Also the returned flux from the target is closer to the oceanic background for a given target albedo. The returned flux for a target with A = 0.02 is only slightly above the background. Again it is found that the returned flux from the target can be discriminated from the background with equal ease no matter what the target distance provided the very weak returned signals can be detected and provided the background from the laser source is larger than the background from natural light sources.

The ocean has been assumed a homogeneous medium in the three cases studied here. How do inhomogeneities in the real ocean influence these

results? Can oceanic layers with different optical properties be distinguished by this method? Several additional calculations were made to study inhomogeneities in the ocean. In all cases the target was placed at 50 m. For comparison the results of the previous calculation with $\beta_{T,R}/\beta_T = 0.5$ are shown as squares in Fig. 4.

In the first inhomogeneous model it is assumed that $\beta_{T,R}/\beta_T = 0.5$ from $0 < z < 25$ and from $30 < z < 50$ m, and $\beta_{T,R}/\beta_T = 0.2$ from $25 < z < 30$ m. The distance z is measured from the source and detector. This model represents a turbid layer in the ocean over the range $25 < z < 30$ m. The results shown by open circles show that the returned flux shows an appreciable increase as the photon path length increases through 60 m (the total distance from source to boundary of turbid layer back to detector). The flux then decreases more rapidly than previously through the turbid layer. When the photon path length is greater than 60 m the slope of the curve approaches its previous value, but the value of the returned flux is now appreciably below the corresponding values for the homogeneous case because of the increased absorption by the turbid layer. This turbid layer noticeably alters the oceanic background and could easily be detected.

The second inhomogeneous model is the same as the first except that the turbid layer is assumed from $40 < z < 50$ m. The returned flux agrees with the homogeneous model up to a photon path length of 80 m. At this point the returned flux abruptly increases and then falls below the homogeneous model. The returned flux from the target is also indicated in Fig. 4. In all cases given here a target with A = 0.02

could be distinguished from the oceanic background.

The third inhomogenous model has five different layers each with its own optical properties. The aim here was to investigate the influence of a more nearly continuous variation in the optical properties of the ocean. The assumed properties of the layers were: $\beta_{T,R}/\beta_T = 1/2$, $0 < z < 10$ m; $\beta_{T,R}/\beta_T = 1/3$, $10 < z < 20$ m; $\beta_{T,R}/\beta_T = 1/4$, $20 < z < 30$ m; $\beta_{T,R}/\beta_T = 1/5$, $30 < z < 40$ m; $\beta_{T,R}/\beta_T = 1/6$, $40 < z < 50$ m. At the first boundary (photon path length of 20 m) the returned flux increases at first and the absolute value of the slope of the curve also increases. The same effect occurs at each boundary, although on a decreasing scale as the relative change in the properties of the water is less at each boundary. The result is to change the slope of the returned flux curve at each of the boundaries. A measurement of the slope of this curve provides information about the local optical properties of the water.

The importance of multiple scattering in the calculation of the returned flux depends greatly on the parameters of the problem. In general multiple scattering is more important the more turbid the water and the larger the photon path length. When $\beta_{T,R}/\beta_T = 1/2$ the ratio of the returned flux including multiple scattering to the single scattered flux is about 1.1 at a photon path length of 40 m and about 1.5 at 100 m. When $\beta_{T,R}/\beta_T = 1/14$ the same ratio is about 1.1 at a photon path length of 4 m, 1.5 at 10 m, and 3.0 at 20 m.

Conclusion

When the surface albedo of a target is greater than about 0.02 it can be detected at any distance in theory by a measurement of the returned flux from a laser as a function of the photon path length (proportional to the delay time). In practice the detection distance is limited by the lowest flux which can be measured and by the background from natural light sources. The slope of the curve for the returned flux as a function of the photon path length varies with the turbidity of the water. An optically inhomogeneous ocean causes measurable changes in either the value or the slope of the returned flux curve.

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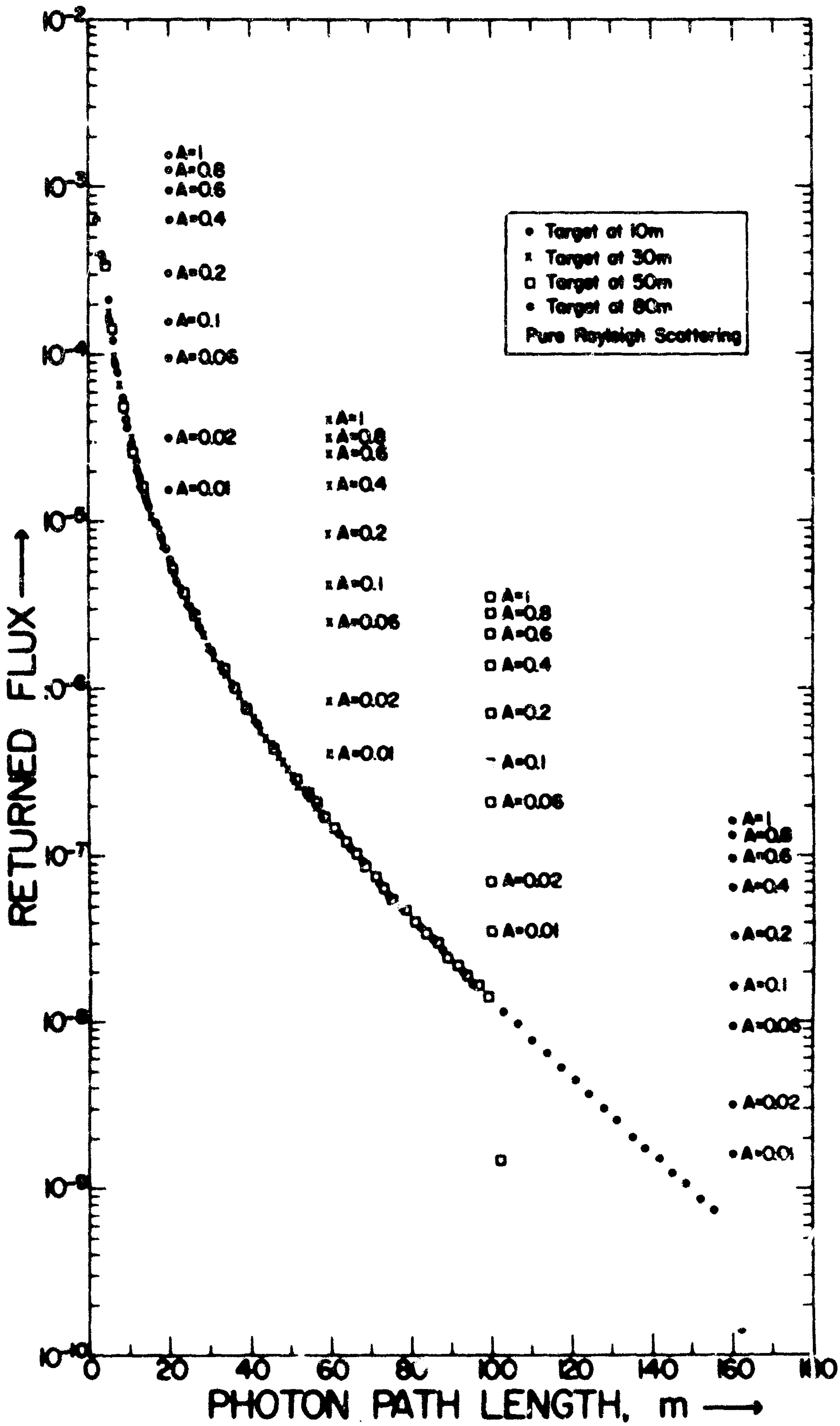
13

Figure 1

The returned flux from a laser source as a function of the photon path length in meters. The half angle of the source and detector are 10^{-3} radians and 5×10^{-3} radians respectively. Calculated points are shown for the returned flux including all orders of multiple scattering for targets at 10, 30, 50, and 80 m. The returned flux from the target is shown for various assumed values of the surface albedo (A). The returned flux is normalized pe. unit flux from the source and per meter of photon path length. Only Rayleigh scattering is taken into account.

14



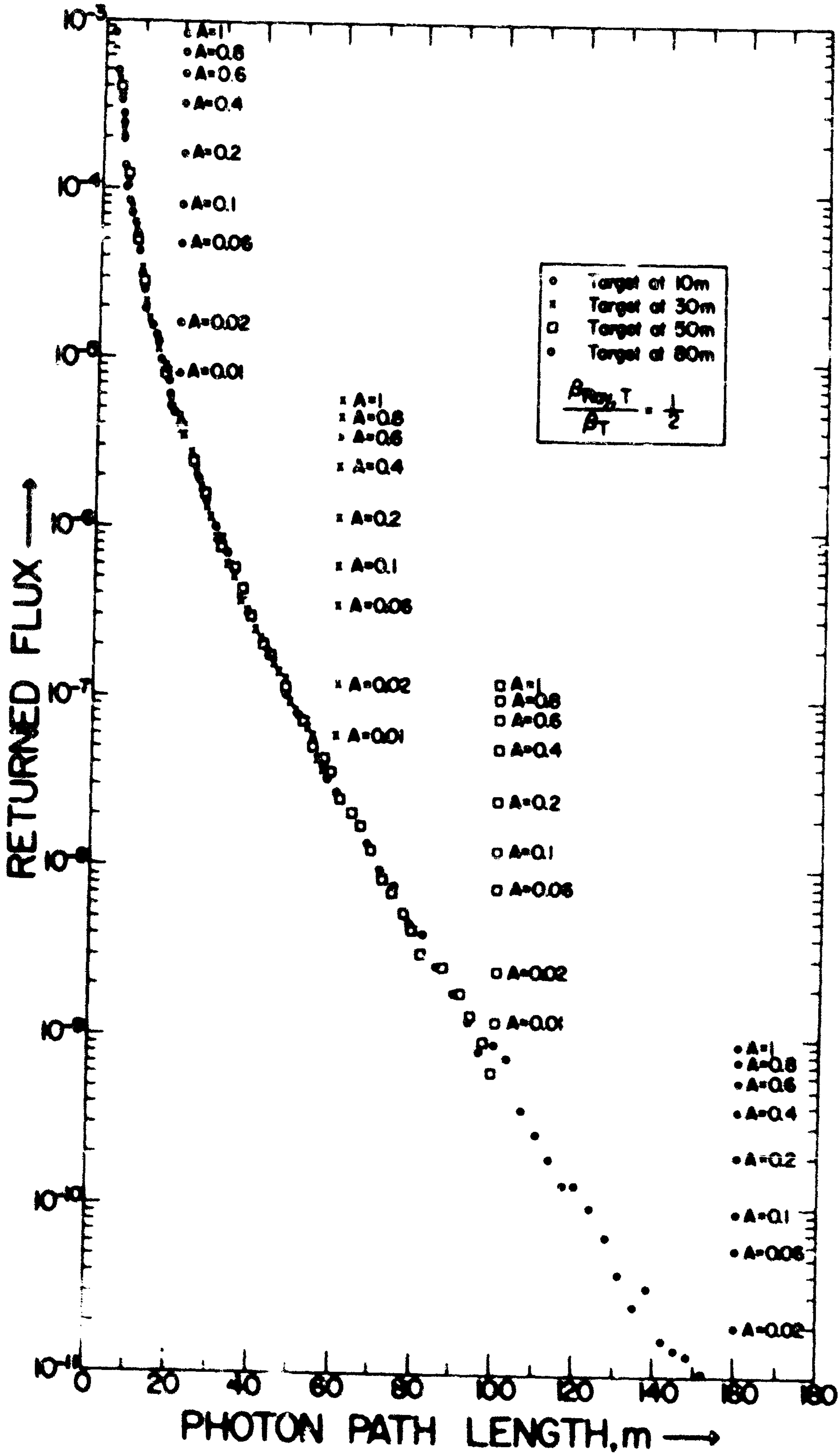
Target at 10m
Target at 30m
Target at 50m
Target at 80m
Pure Rayleigh Scattering
RETURNED FLUX ⟶
PHOTON PATH LENGTH, m ⟶
A=1
A=0.8
A=0.6
A=0.4
A=0.2
A=0.1
A=0.06
A=0.02
A=0.01

Fig. 1

Figure 2

Returned flux as a function of photon path length in meters. Both Rayleigh and hydrosol scattering centers are assumed. The ratio of the total Rayleigh attenuation length ($\beta_{T,R}$) to the total attenuation length from both Rayleigh centers and hydrosols (β_T), $\beta_{T,R}/\beta_T = 1/2$. See caption to Fig. 1.

16



RETURNED FLUX
PHOTON PATH LENGTH, m
Target at 10m
Target at 30m
Target at 50m
Target at 80m
A=1
A=0.8
A=0.6
A=0.4
A=0.2
A=0.1
A=0.06
A=0.02
A=0.01

Figure 3

Returned flux as a function of photon path length in meters. $\beta_{T,R}/\beta_{\bar{T}} = 1/14$. Targets are assumed at 2, 5, and 10 m. See caption to Fig. 1.

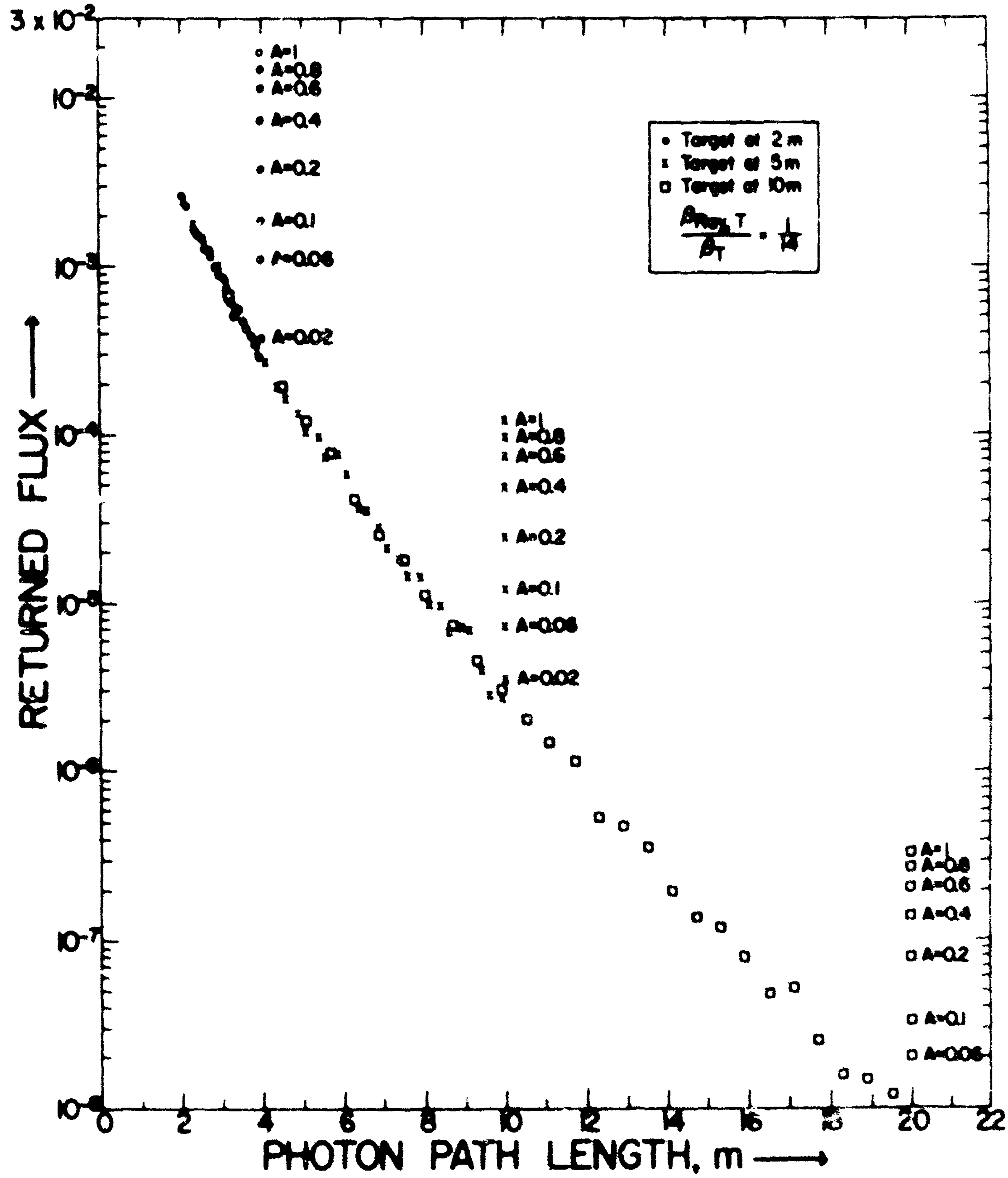
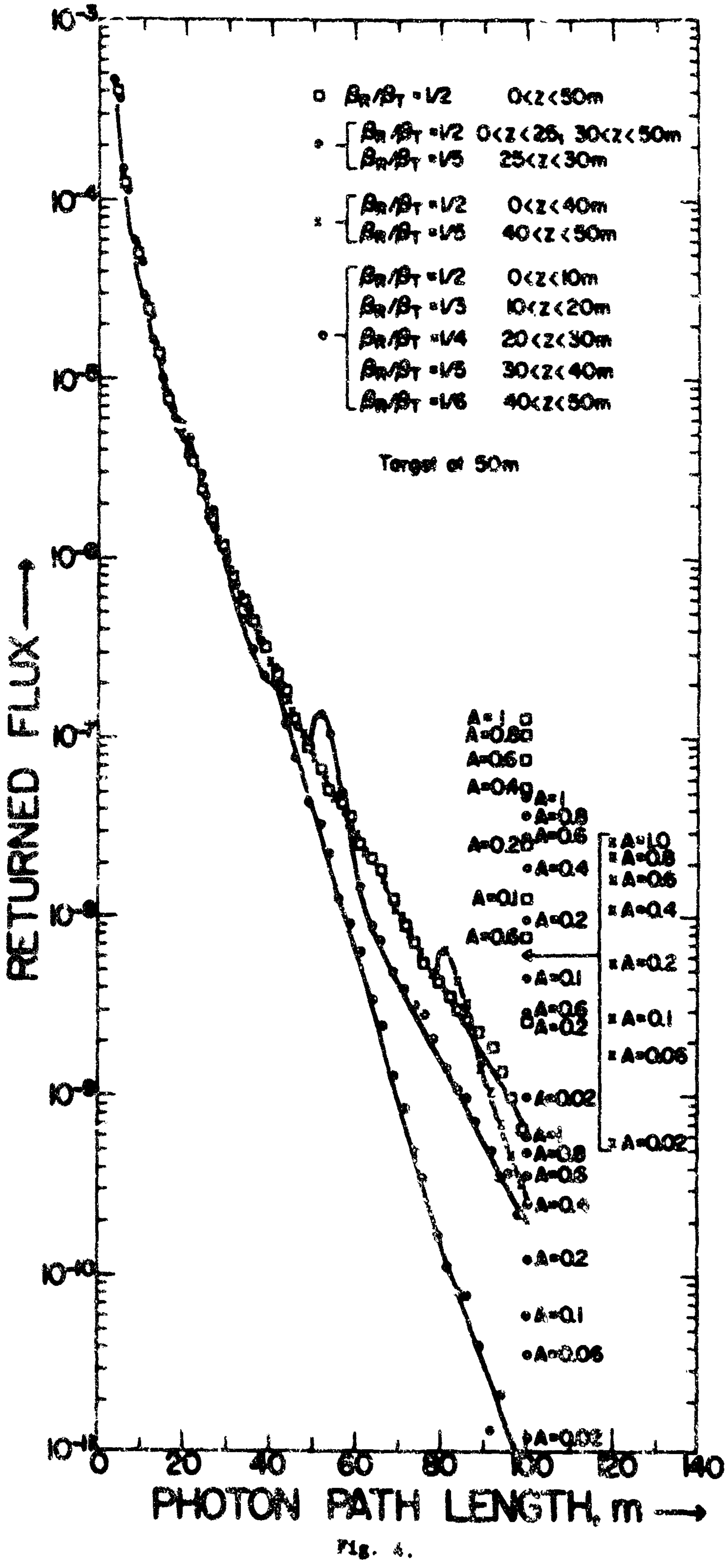

3 x 10^-2
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
RETURNED FLUX
PHOTON PATH LENGTH, m
0 2 4 6 8 10 12 14 16 18 20 22
Target at 2 m
Target at 5 m
Target at 10m
A=1
A=0.8
A=0.6
A=0.4
A=0.2
A=0.1
A=0.06
A=0.02

Fig. 3

19

Figure 4

Returned flux as a function of pho[illegible] path length in meters. The target is assumed at 50 m. Calculated points for a homogeneous ocean with $\beta_{T,R}/\beta_T = 1/2$ are indicated by squares. Open circles are the same except for a turbid layer ($\beta_{T,R}/\beta_T = 1/5$) from $25 < z < 30$ m, where z is the distance from the source. Crosses are the same model, except the turbid layer is from $40 < z < 50$ m. Solid circles indicate a model with five different layers, each with different optical properties: $\beta_{T,R}/\beta_T = 1/2$, $0 < z < 10$ m; $\beta_{T,R}/\beta_T = 1/3$, $10 < z < 20$ m; $\beta_{T,R}/\beta_T = 1/4$, $20 < z < 30$ m; $\beta_{T,R}/\beta_T = 1/5$, $30 < z < 40$ m; $\beta_{T,R}/\beta_T = 1/6$, $40 < z < 50$ m. See caption to Fig. 1.



□ βR/βT = 1/2 0<z<50m
• βR/βT = 1/2 0<z<25, 30<z<50m
βR/βT = 1/5 25<z<30m
x βR/βT = 1/2 0<z<40m
βR/βT = 1/5 40<z<50m
○ βR/βT = 1/2 0<z<10m
βR/βT = 1/3 10<z<20m
βR/βT = 1/4 20<z<30m
βR/βT = 1/5 30<z<40m
βR/βT = 1/6 40<z<50m
Target at 50m
RETURNED FLUX
PHOTON PATH LENGTH, m

Fig. 4.